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Research paper

Experimental identification of dynamic characteristics of a track structure influencing the level of noise emission

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Abstract: The present paper describes an experimental methodology of identification of dynamic characteristics of a track structure, consisting in determination of a track decay rate (TDR) in the field tests that were conducted by the authors on the railway line section in Warsaw. The proposed methodology of measurements, parameters determination and presentation of the results is based on the measurement methods described in EN 15461 [1], which are aimed at determination of TDR. The values of TDR determined in the impulse tests in one-third octave bands are compared with the limiting values specified in EN ISO 3095 [2] and Technical Specifications for Interoperability (TSI) [3]. Based on the obtained experimental data, the analysed railway line is classified as a structure that does not generate excessive level of rolling noise from the vibrations induced by the moving rolling stock on structural elements of the track – particularly on rails. The results obtained in this study are promising from the point of view of future development of effective solutions used for protection of people and environment against noise generated by the railway traffic.

Keywords: track structure, track decay rate, impulse tests, field tests, dynamic characteristics

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1. Introduction

The latest trends in rail transport assume the best possible usage of route capacities, for example by increasing the trains velocity and, as a result, reducing the travel time. There are, however, some negative effects of such trends, among others an increased level of noise emitted to the environment. It affects well-being of people, reduces their work productivity, concentration and general life quality.

The process of noise generation in railway systems is a very complex phenomenon. It is caused mainly by the rolling noise, which is induced by the rolling stock that moves along the rails. There are numerous irregularities on the rolling surfaces of the wheels and rails (for example wave shape of rails), which induce vibrations of both the rolling stock and rails, thus generating noise emitted to the environment. Apart from the vibrations caused the rolling surfaces of wheels and rails, the noise is also generated by the aerodynamic resistance of the stock and several other sources, such as the engine or the pantograph slipping along the contact lines.

In order to minimize such negative influences, various solutions may be used. In the emission zone, that is in the contact zone between wheels and rails, irregularities of the rolling surfaces should be removed by profiling the rails (e.g. grinding) and the wheels (e.g. lathing). Another method that can be used for the reduction of the acoustic wave emission, consists in optimization of elastic properties of the track structure – particularly the elastic support and fastening of rails – by applying additional elements and structural layers. Such elements, apart from fulfilling mechanical functions of transferring dynamic loads from the rolling stock, can be used as vibroacoustic isolators that reduce the vibration transmission between parts of the track structure – mainly the rail fastening systems [4, 5]. Other elements, which are used in track structures to reduce the noise emission level, are dampers. Depending on their location in the track system, they are called either track absorbers or rail dampers [6].

Many methods for assessing the performance of rail dampers can be found in the literature. There is a group works [7–9] that describe a Franco-German research project STARDAMP, whose target was to support the transfer from research and development of rail and wheel dampers to their regular application. In [9] the authors presented a software tool developed within STARDAMP, which is dedicated to the prediction of the efficiency of wheel and rail dampers. Another method for the prediction of track decay rates (TDR) was described by Betgen [10] and is based on the finite element modelling (FEM).

In [11] Margiocchi et al. summarized the results of a work program launched in 2002, which was aimed at putting in service on the French railway network several monitoring products. They used an assessment method developed in STARDAMP, which combines laboratory measurement and simulation model and gives an accurate prediction of the noise reduction.

Squicciarini et al. [12], on the other hand, described experimental procedures for assessing the performance of rail dampers. They conducted laboratory measurements of vertical and lateral decay rates on a free rail equipped with dampers. In [13] Haladin et al. estimated the rail-track vibration damping level, as one of key properties for determining proportion of rail track influence in the total rail traffic noise and vibration levels. Qian et al. [14] studied the effects of a rail vibration absorber on suppressing short pitch rail corrugation. They conducted field tests and used two finite element models of a wheel-rail system and a wheel-rail-absorber system.

In [15] Michalczyk et al. proposed a concept and presented preliminary results of numerical study of changes in the rail track dynamic characteristics. They used FEM modelling for the standard test simulation. The study revealed correlation between the railroad track mass increase and its dynamic characteristics and thus the noise emission. Zoontjens et al. investigated rolling noise emissions from trains operating on the Perth electrified passenger network [16]. They compared STARDAMP model results with field measurements for ballasted and slab track with and without rail dampers. It was proved that the noise from the train network can be effectively attenuated using rail dampers.

An interesting solution was proposed by Koller et al. in [17], where the authors discussed a rail web shielding technology named Calmmoon Rail. Field trials in Germany and Switzerland showed reductions in the overall noise level of the rail infrastructure of up to 4.4 dB.

There are several works that focus on measurement methods used for identification of dynamic characteristics of track structures. Burdzik et al. [18] researched the influence of impulse force on vertical vibration of the rail. Sołkowski et al. [19] studied the analogies between road and railway and proposed a new method for measuring and assessing characteristics of track structures, based on Falling Weight Deflectometer (FWD). Kogut et al. [20] used impulse functions as a tool for identifying dynamic parameters of the subgrade.

The present paper describes an experimental methodology of identification of dynamic characteristics of a track structure, consisting in determination of a track decay rate (TDR) in the field tests that were conducted by the authors on the railway line section in Warsaw. The proposed methodology of measurements, parameters determination and presentation of the results is based on the measurement methods described in EN 15461 [1], which are aimed at determination of TDR. The values of TDR determined in the impulse tests in one-third octave bands are compared with the limiting values specified in EN ISO 3095 [2] and Technical Specifications for Interoperability (TSI) [3].

2. Theory and standard procedures

Dynamic characteristics of the track structure analyzed in this work (TDR) are defined in detail in EN 15461 [1]. Impulse testing is aimed mainly at verification of the predicted influence of particular elements of the track structure on the value of TDR. TDR value is correlated with the level of noise emission, as there is a strong relationship between TDR and the intensity of the rolling noise emitted by the track elements (e.g. rails).

Contact between the wheel of a moving train and the rail induces vibrations of both the train and the elements of the track structure. High frequency vibrations (ca. $100 \div 5000$ Hz) generate unfavorable acoustic waves perceived as noise. The main source of such sounds are vibrations of the elements located directly in the contact area between wheels and rails. Dynamic response of the track structure (especially rails) is crucial due to its significant participation in the rolling noise.

Rail vibrations consist of vertical and horizontal oscillations of the rail, treated as a beam bended in two directions. Although such vibrations are not responsible for all measured frequencies, this simplification makes it possible to apply a concept of damping decrements and thus to simulate dynamic characteristics of the track structure.

The relation between TDR and the effectiveness of the rolling noise damping has strong theoretical foundations. Their presentation requires an introduction of several terms. One of the most important parameters is a frequency response function (FRF). It is a frequency-dependent ratio of an output response to a stimulus (excitation). In the discussed study both velocity and acceleration can be used as measured parameters (here the vertical and horizontal acceleration measurements were performed).

Using this function, a ratio between the acceleration amplitude in the excitation point (e.g. hammer impact) and the acceleration amplitude in a point located at a distance of x [m] from the excitation point can be determined. The function is dependent on both the distance between the points and the frequency of pulse excitation. In a discreet approach, the described dependence is averaged within one-third octave bands and the parameters of function series dependent only on the distance from the excitation point are searched for.

Assuming that $A(x)$ corresponds to the amplitude of the FRF in a one-third octave band at a distance of $x$from the excitation point, the noise emitted by the rail is proportional to the FRF integrated along the length of the rail and to the velocity of vibrations in the excitation point $\int_0^\infty |A(x)|^2 \,\mathrm{d}x$. If additionally $A(x) \approx A(0) \cdot e^{-\beta x}$ (assuming that the vertical and lateral waves decrease with an increase of x), it can be proved that the noise emission in each octave band equals $|A(x=0)|^2 /2\beta$, where β is a constant decay of the response amplitude A. The decay rate TDR [dB/m] is proportional to β: TDR $= 20\log\left(e^{\beta}\right) = 8.686\beta$. In practice TDR is estimated based on n measurements of accelerations at different distances x:

$$\int\limits_0^\infty \frac{|A(x)|^2}{|A(x_0=0)|^2}\,\mathrm{d}x = \frac{1}{2\beta} \approx \sum_{n=0}^{n_{\max}} \frac{|A(x_n)|^2}{|A(x_0)|^2}\Delta x_n \tag{2.1}$$

where: x_n – a set of points at which the response is sampled, $n_{\max}$ – a measurement corresponding to the point at the maximum measuring distance, Δx_n – an interval between the points situated at half-distance between the measuring positions.

Field tests of dynamic characteristics of the track consist in exciting the track structure using an excitation device, usually an impact hammer, as indicated in EN 15461 [1]. Dynamic characteristics are determined based on the track response in the measurement section (accelerations), which arouse as a result of an excitation impulse at various distances from the excitation point. The accelerations are measure vertically and laterally, correspondingly to the applied impulse. During the tests several parameters are measured: impulse characteristics, impulse force, its variability in time and the response in the form of acceleration functions. Due to the fact that this method is prone to human error, at least four impulses are applied in each excitation point and the average is taken. If the coherence of each impulse/measurement is correct, the authors usually use the linear average. Afterwards, the obtained data are processed and the results are presented according to the requirements of the standard EN 15461 [1].

There are many additional analyses performed during the measurements, which can be indirectly used to assess dynamic characteristics of the track, for example to determine eigenfrequencies of the system. Registered signals can be distributed not only in the time domain, but also in the frequency domain using a FFT analyser. In this way, it is possible to indicate ranges of frequencies for which the highest vibration amplitudes are reached, thus the frequencies which are most important from the acoustic point of view.

3. Description of the tested section

3.1. Railway line section

Before the measurements, the authors conducted a local vision of the terrain along the analyzed railway line section located in Warsaw (LK-501) in order to choose the exact location for tests, which would fulfil the requirements of EN 15461 [1]:

– it should be located at a distance from any infrastructure that could affect the measurements,
– structural parameters of the track should be constant over the whole test section,
– there should be no rail welds or rail expansion joints,
– the accelerometers should be installed at least 20 m from the centre of the test section, at a median point of a space between the sleepers, they should not be located close to rail supports.

The TDR measurements were conducted on the temporarily closed section of railway line no. 501, track no. 1 in Warsaw. The chosen location is free from untypical track infrastructure. The tested track is a one-track railway line on a 4.5 ÷ 6.5 m high embankment. There are no strong vibroacoustic sources in the close proximity (the closest road is located 25 m from the track axis). The tested section is straight, the track axis is located along the east-west direction. Rail no. 1 is located at the northern side of the track (N), rail no. 2 – at the southern one (S). Fig. 1 presents the tested section, prior to installation of accelerometers and determination of measurement points.

a) b)

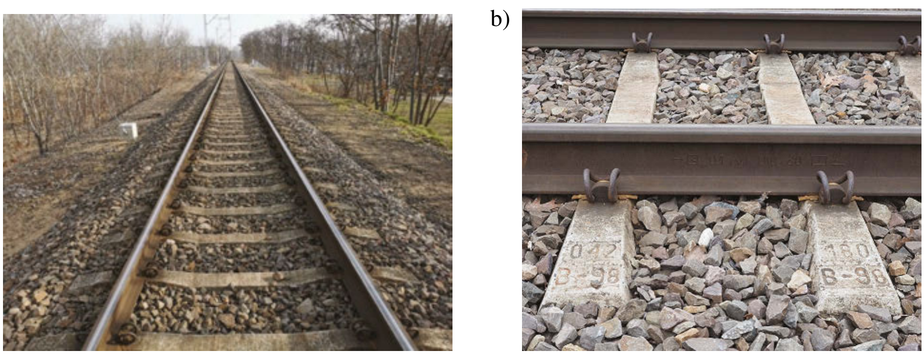

Fig. 1. Test section selected for TDR tests: a) view along the section; b) closer view of the ballasted track structure

The adopted scheme of excitation points location is depicted in Fig. 2. There were 29 measurement points, the first one was located in a direct proximity to the test section, the 29th one – at a distance of 36.9 m, the points were marked from $i = 1$ to $i = 29$. The excitation points were located in the east direction toward the test section. The test field selected for the TDR tests is presented in Fig. 3.

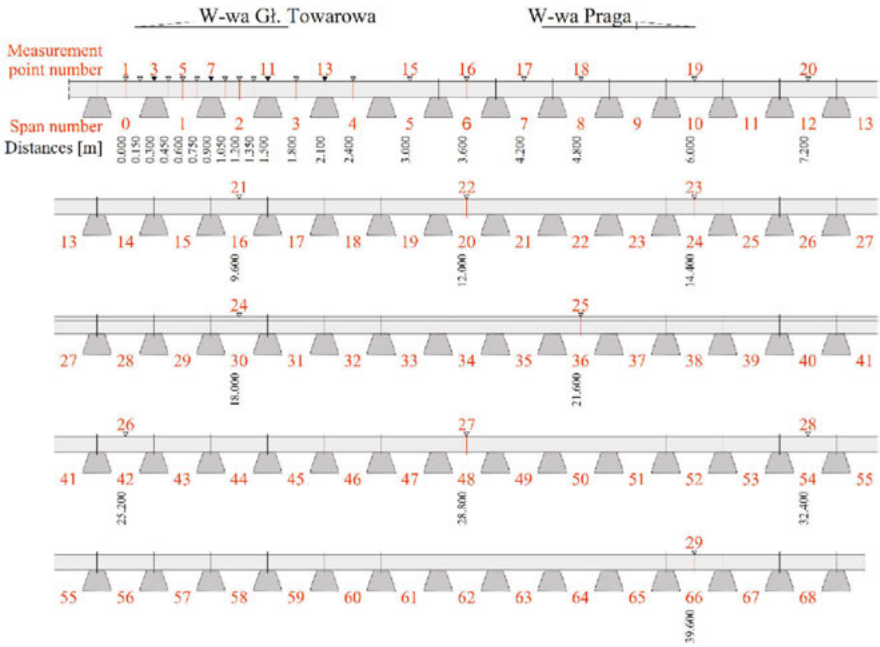

Fig. 2. Location of rail excitation points

a)  b) 

Fig. 3. Test field with marked sections selected for TDR tests: a) location of impulse excitation points, marked with yellow chalk; b) field ready for tests

3.2. Technical condition of the track structure

The track structure underwent a complex modernization in 1998 (determined based on concrete sleepers stamping) and additionally, in December 2020, the system was regulated by adjusting the track geometry in vertical and horizontal planes. Technical characteristic of the ballasted track structure over the analyzed section of LK-501 is presented in Table 1.

During the inspection of the test section, no significant damages of the track elements were identified (no significant vertical or lateral wear of the rail head, no traces of wave wear of the rail head, no damages in concrete of the sleepers, no damages of the rail fastening system,

Table 1. Technical characteristics of the ballasted track structure over the tested section of LK-501

Track class	1, jointless track
Track structure standard	1.1
Vignoles rail	UIC 60 (corresponds to 60E1)
Rail fastening system	under rail pad PKW 60 K, elastic rail clip SB4, insulator WKW60 with TSK-2
Sleepers	prestressed concrete sleepers type PS-83, spacing 0.6 m
Ballast	thickness 0.35 m, melaphyre 31.5/50

no ballast pollution). Technical condition of the analyzed track structure was assessed by the authors as good.

4. TDR measurements

4.1. Measurement system

The measurement system consisted of: accelerometers, impact hammer, data acquisition system and a PC with the data processing software, as required by EN 15461 [1]. Accelerometers were installed on the rails: for the measurements of vertical vibrations decay – at the top of the rail head and along the rail axis; for the measurements of horizontal vibrations decay – on the side surface of the rail head at the side of the track axis. During the measurements, only accelerations corresponding to the tested direction were registered. Fig. 4 presents pictures of sensors installed on rail no. 1 (N).

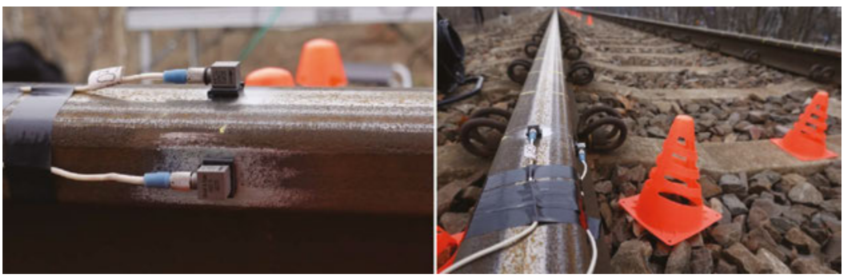

Fig. 4. Sensors installed on the rail during the TDR tests

4.2. Scenario and procedure of measurements

The measurement scenario was prepared according to EN 15461 [1]. There were eight measurement series, four series per rail (two in vertical and two in horizontal direction). Each series was preceded by a measurement system check and a calibration measurement of the hammer that consisted of minimum four hammer impacts applied as close to the measurement section as possible.

Each measurement series consisted of minimum four correct excitation impulses applied in each of 29 excitation points, which gives $4 + (29 \cdot 4) = 120$ correct hammer impacts per series. A correct hammer impact should be understood as an impact that excites the system to the assumed frequency spectrum, exhibits a repetitive characteristic of the force impulse and a good coherence.

Fig. 5 presents an impulse excitation during the measurements of TDR in a close proximity to the measurement section.

Fig. 5. Impulse excitation in the TDR test (left side: vertical, right side: horizontal)

5. Results

In this section, the authors present selected results of the measurements of dynamic characteristics of the track structure, using the previously described TDR method. Two values were registered during the tests: accelerations and impulse force as functions of time. In the tests, the frequency range of $10 \div 12800$ Hz was considered. In order to compare the results, the measurements conducted in four excitation points are presented: 1 ($x = 0.0$ m), 14 ($x = 2.4$ m), 24 ($x = 18.0$ m), 29 ($x = 36.9$ m). Fig. 6 depicts time waveforms from impact force sensors

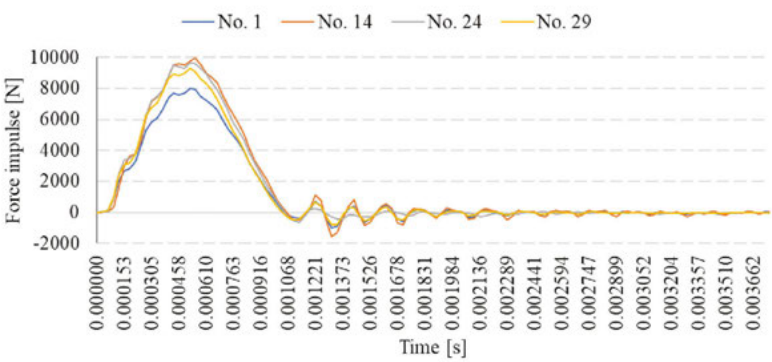

Fig. 6. Force impulse in the time domain registered by impact force sensors – vertical excitations in points 1, 14, 24 and 29

registering vertical hammer impacts. The authors achieved a repetitive excitation characteristic and a force variability between 8.0 ÷ 9.0 kN.

Vertical accelerations in the time domain are depicted in Fig. 7. It can be noticed that the sensor excitations are shifted depending on the distance between the excitation point and the measurement section (x = 0.0 m). Moreover, the vibration amplitudes decrease significantly for higher x values.

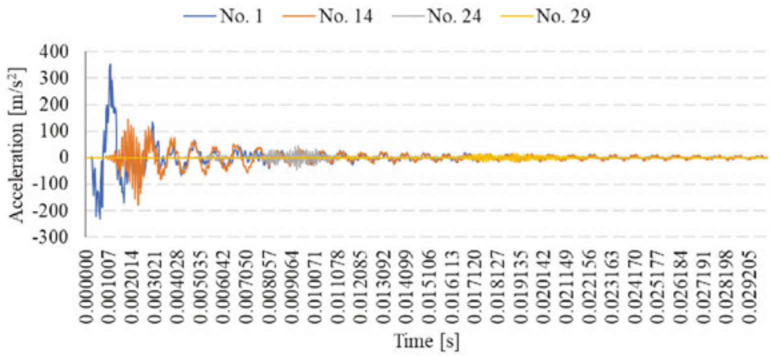

Fig. 7. Accelerations in the time domain – vertical excitations in points 1, 14, 24 and 29

Fig. 8 depicts the FRF function for vertical excitations in selected points. An effect of vibrations mobility for frequencies higher than 4 kHz is observed.

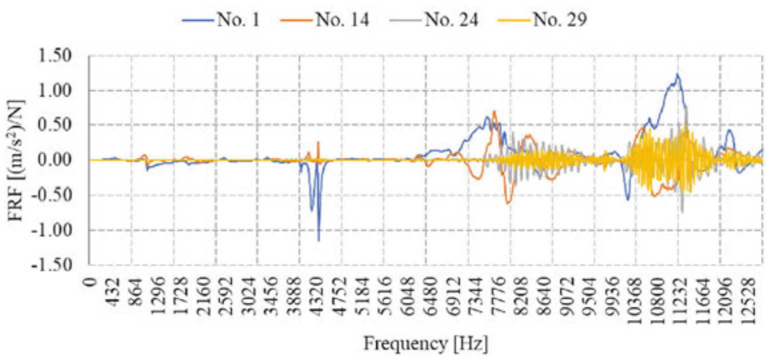

Fig. 8. Frequency response function (FRF) – vertical excitations in points 1, 14, 24 and 29

Fig. 9 presents results of the FFT analysis of vibration accelerations for vertical excitations. An effect of intensive vibrations in the frequency range of 500 ÷ 1200 Hz is observed for small values of x (it lies within the audio frequency range). Additionally, an effect of significant vibrations mobility for frequencies higher than 4 kHz is noticeable.

Fig. 10 depicts time waveforms from impact force sensors registering horizontal hammer impacts. The authors managed to achieve a repetitive excitation characteristic (hammer impacts on the side surface of rail head) and a force variability between 4.0 kN and 7.0 kN.

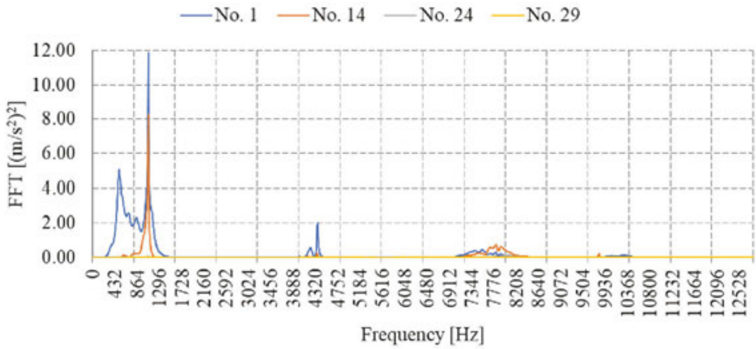

Fig. 9. FFT analysis of vibration accelerations – vertical excitations in points 1, 14, 24 and 29

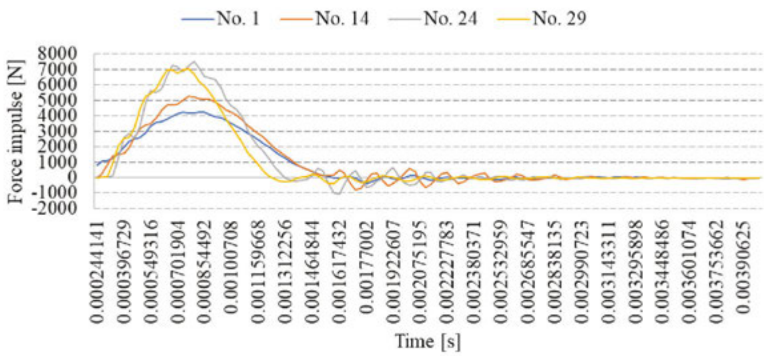

Fig. 10. Force impulse in the time domain registered by impact force sensors – horizontal excitations in points 1, 14, 24 and 29

Horizontal accelerations in the time domain are depicted in Fig. 11. It can be noticed that the sensor excitations are shifted depending on the distance between the excitation point and the measurement section ($x = 0.0$ m). Moreover, the vibration amplitudes decrease significantly for higher x values.

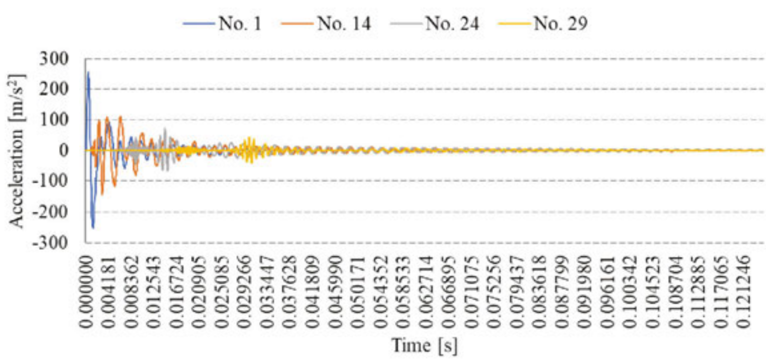

Fig. 11. Accelerations in the time domain – horizontal excitations in points 1, 14, 24 and 29

Fig. 12 depicts the FRF function for horizontal excitations in selected points. An effect of vibrations mobility for frequencies higher than 5 kHz is observed.

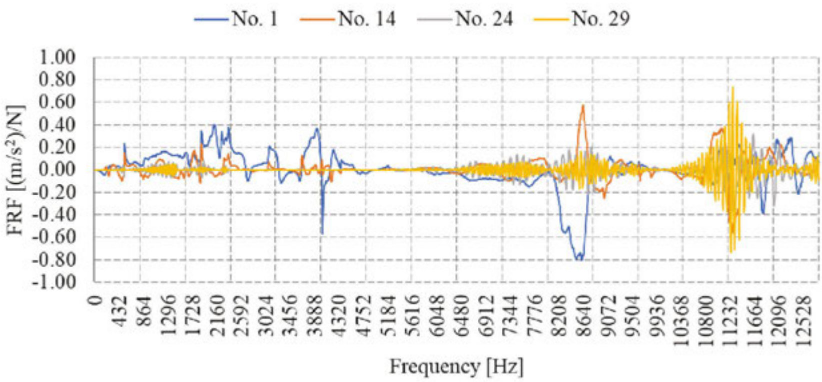

Fig. 12. Frequency response function (FRF) – horizontal excitations in points 1, 14, 24 and 29

Fig. 13 presents results of the FFT analysis of vibration accelerations for horizontal excitations. Effects of intensive vibrations and significant vibrations mobility in the frequency range of 150 ÷ 1500 Hz are observed for small values of x (it lies within the audio frequency range).

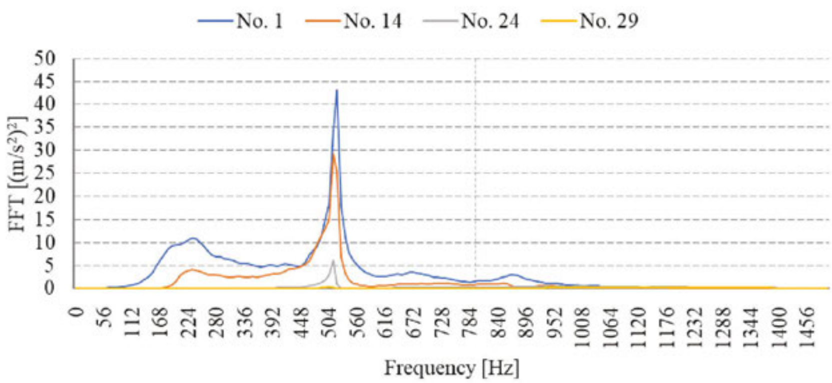

Fig. 13. FFT analysis of vibration accelerations – horizontal excitations in points 1, 14, 24 and 29

Below, the authors present two (out of eight realized measurement series) selected results of the TDR tests – TDR values in one-third octave bands for the frequency range of 100 ÷ 5000 Hz. Fig. 14 depicts TDR graphs obtained for the vertical plane, Fig. 15 – for the horizontal plane. There are two curves on both graphs: the blue one indicates the values of TDR measured during the field tests, the orange one – the minimum values of TDR calculated according to EN ISO 3095 [2] and TSI [3].

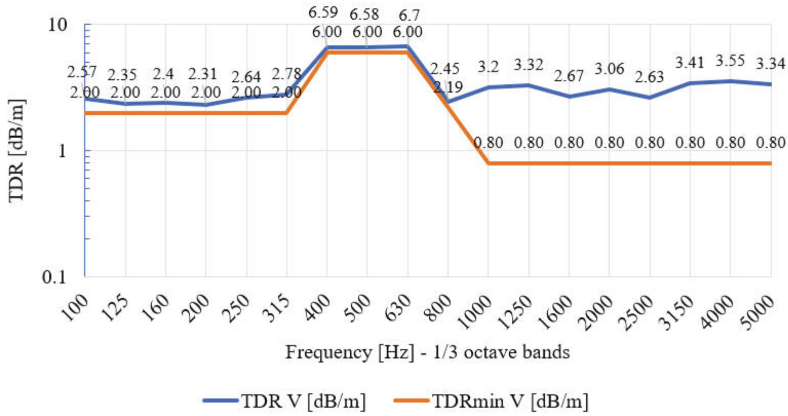

Fig. 14. Track decay rate (TDR) in vertical (V) plane – measurements series no. 2, rail no. 1 (N)

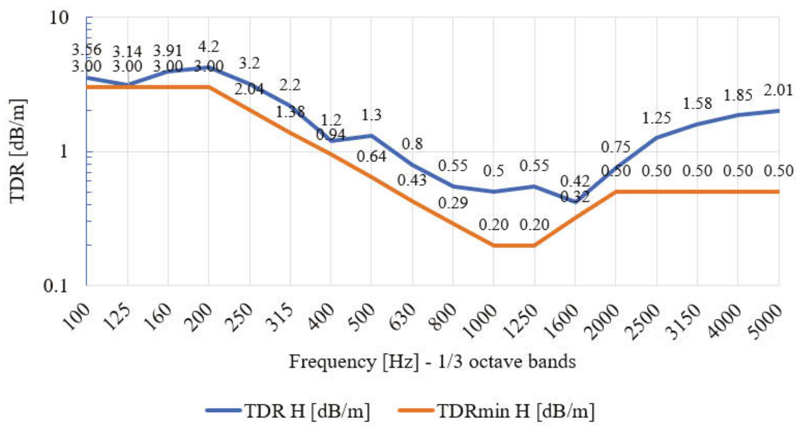

Fig. 15. Track decay rate (TDR) in horizontal (H) plane – measurements series no. 3, rail no. 1 (N)

6. Conclusions

In the present paper the authors focused on determination of a track decay rate (TDR) using the dynamic characteristics measured in the impulse field tests conducted on the railway line section in Warsaw. The values of TDR obtained for one-third octave bands were compared with the limiting minimum values required by the standard EN ISO 3095 [2] and Technical Specifications for Interoperability (TSI) [3]. Based on the TDR graphs presented in the previous section and similar values of TDR obtained in six other measurement series, it can be stated that the tested track fulfills the requirements of [2] and [3] within its dynamic characteristics.

Obtained experimental data allowed the authors to qualify railway line LK-501, analyzed over the selected test section, as a railway line that does not generate excessive rolling noise from the vibrations excited in track elements (especially in rails and rail fastening system) by the moving rolling stock. The values of TDR, which are higher than the minimum values required, indicate that the elements of the track structure (such as the under rail pad and rail clips) were designed properly. It was additionally stated in the visual inspection, where no damages and no significant wear were identified.

Results of TDR tests make it possible to assess dynamic characteristics of railway track structures (for example eigenfrequencies) and to understand and simulate the phenomena which cause noise emissions. In the future, it may lead to more effective solutions used for protection of people and environment against noise from the railway traffic.

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Doświadczalna identyfikacja charakterystyk dynamicznych nawierzchni kolejowej wpływających na poziom emisji hałasu

Słowa kluczowe: nawierzchnia kolejowa, współczynnik zanikania drgań, badania impulsowe, badania poligonowe, charakterystyki dynamiczne

Streszczenie:

W artykule przedstawiono doświadczalną metodykę badawczą wyznaczania charakterystyk dynamicznych nawierzchni kolejowej poprzez badania poligonowe współczynnika zanikania drgań wzdłuż szyny zrealizowane przez autorów na odcinku linii kolejowej w Warszawie. Jako podstawę w odniesieniu do metodologii pomiaru, wyznaczenia i prezentacji wyników wykorzystano metodykę pomiarową opisaną w normie europejskiej EN 15461, której celem jest wyznaczenie współczynnika zanikania drgań wzdłuż szyny (ang. *Track Decay Rate*, w skrócie TDR).

Najnowsze trendy w transporcie szynowym, zakładają jak największe wykorzystanie przepustowości tras m.in. poprzez wzrost prędkości pojazdów, a tym samym skrócenie czasu przejazdu. Negatywnym skutkiem takich działań jest jednak m.in. zwiększenie poziomów emisji hałasu do środowiska. W przypadku ludzi ma to ujemny wpływ na ich zdrowie, zmniejsza wydajność pracy, utrudnia wypoczynek i koncentrację, a więc ogólnie, zmniejsza komfort życia w strefie takich oddziaływań.

Aby zminimalizować te negatywne oddziaływania stosuje się różne rozwiązania, które w strefie emisji, tj. strefie kontaktu kół i szyn polegają m.in. na usuwaniu nierówności na ich powierzchniach tocznych poprzez profilowanie szyn oraz kół. Innym sposobem ograniczania emisji fali akustycznej są działania podejmowane w konstrukcji drogi kolejowej, polegające na optymalizacji sprężystych charakterystyk tej konstrukcji – głównie sprężystego podparcia i mocowania szyn poprzez zastosowanie odpowiednich elementów i warstw konstrukcyjnych. Oprócz funkcji mechanicznych związanych z przenoszeniem dynamicznych obciążeń od ruchu pojazdów szynowych, elementy te spełniają funkcje izolatorów wibroakustycznych, które ograniczają transmisję drgań pomiędzy elementami składowymi konstrukcji nawierzchni szynowej – głównie elementami systemów przytwierdzenia szyn.

W niniejszej pracy przedstawiono wyniki badań poligonowych, w ramach których mierzono metodą impulsową współczynnik TDR. Badania przeprowadzono na czasowo zamkniętej łącznicy wzdłuż linii kolejowej nr 501, tor nr 1 w Warszawie. Celem badań była przede wszystkim weryfikacja przewidywanego wpływu elementów składowych nawierzchni kolejowej na wartość współczynnika TDR. Wartość tego parametru pozwala wnioskować o poziomie emisji hałasu, ponieważ istnieje silny związek pomiędzy współczynnikiem TDR a intensywnością emisji hałasu toczenia przez elementy składowe nawierzchni kolejowej (np. szyny).

Wyznaczone metodą impulsową w badaniach terenowych wartości współczynnika TDR w tercjowych pasmach częstotliwości odniesiono do wartości granicznych określonych w normie europejskiej EN ISO 3095 oraz Technicznych Specyfikacjach Interoperacyjności (TSI). Na bazie wyników badań empirycznych zakwalifikowano analizowaną linię kolejową jako nie generującą nadmiernego poziomu hałasu toczenia od drgań elementów składowych nawierzchni kolejowej wzbudzonych przez przejeżdżające pojazdy szynowe.

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